Executive Summary

This report recommends a strategy for making observations of carbon dioxide (CO_2) and related properties in the atmosphere and oceans, over large spatial scales and long timescales. It also recommends process studies of air-sea gas exchange, in order to obtain more accurate estimates of CO_2 transfer between the atmosphere and oceans. Models are essential tools for understanding the distributions and fluxes of CO_2 in the atmosphere and oceans. We recommend observations and modeling efforts to enhance the skills of models used for this purpose. An ultimate product of the observations, modeling efforts, and complementary process studies will be improved projections of the trajectory of the atmospheric CO_2 increase.

The report's recommendations are summarized in Table E-1. These recommendations are prepared in the context of the U.S. Carbon Cycle Science Plan (CCSP),[1] with the goal of advancing our ability to address the two fundamental questions that the CCSP posed:

- What has happened to the carbon dioxide that has already been emitted by human activities (past anthropogenic CO_2)?
- What will be the future atmospheric CO_2 concentration trajectory resulting from both past and future emissions?

The importance of answering these questions is evident. A recent National Research Council report, *Climate Change Science,* documents the consensus scientists have reached that human emissions of greenhouse gases are increasingly affecting world climate.[2] The President's speech to the nation on global climate change[3] expressed concern about greenhouse warming at the highest levels of government and committed the United States to confront the issue. These documents recommend conducting the research necessary to understand the environmental behavior of biogenic greenhouse gases, of which carbon dioxide is the most significant. This research will lead toward the knowledge required to accurately project carbon removal rates from the atmosphere to the land biosphere and the oceans.

This report presents a plan for large-scale U.S.-sponsored observations of CO_2 in the oceans and atmosphere. This plan represents an implementation plan for the CO_2 observations component of the CCSP. We recommend observations to track the fate of fossil fuel-derived CO_2, to characterize fluxes of CO_2 from the atmosphere to the land biosphere and oceans over large scales of space and time, and to achieve process-level understanding of physical and biological controls on those fluxes now and in the future. Complementary small-scale process studies of the land and ocean biospheres are needed for a comprehensive understanding of carbon fluxes and distributions. No specific

[1] Sarmiento, J.L., and S.C. Wofsy (1999): *A U.S. Carbon Cycle Science Plan.* U.S. Global Change Research Program.

[2] National Research Council, Committee on the Science of Climate Change, *Climate Change Science: An Analysis of Some Key Questions,* National Academy Press, 2001; `http://www.nap.edu/`.

[3] Rose Garden; 11 June 2001.

Table E-1: Priorities and cost estimates for atmospheric observation program.

Element of the implementation plan	**Priority**	**One-time Costs**	**Per-year Costs**
Recommendations for the Next 1 to 5 Years			
Improve the quality of existing measurements and support technological development			
Continue existing network	1		\$4,000,000
Robust CO_2 analyzer	1	\$750,000	\$150,000
Quality control and methodology			
CO_2 standards propagation	1		\$50,000
Ongoing intercomparisons	1		\$225,000
CO_2 isotopic calibration scale	1	\$500,000	
$^{13}C/^{12}C$ intercomparisons	1		\$100,000
O_2/N_2 intercomparisons	1		\$100,000
Make intensive and extensive measurements of the vertical distribution of CO_2 over continents			
Intensive measurements of the North American carbon cycle	2		~\$10,000,000 per campaign
Aircraft profiles over continents	2	\$3,000,000	\$7,000,000
Tall tower observations	2	\$2,300,000	\$800,000
Make new global measurements of CO_2 and other species			
Background CO_2 measurements	3		\$800,000
Measurements on pCO_2 platforms	3		\$15,000 per ship
Atmospheric O_2/N_2 measurements	3	\$440,000	\$240,000
$^{13}C/^{12}C$ and $^{18}O/^{16}O$ measurements	3		\$600,000
Robust CO analyzer	3	\$850,000	\$200,000
Recommendations for the Timescale of 6 to 10 Years			
Increase observations of CO_2, its isotopes, O_2/N_2, and related tracers, and their interpretation for global regional-scale CO_2 flux measurements			
100 new continental sites, 20 commercial ship tracks, and 30 mooring installations.		~\$15,000,000	~\$15,000,000

recommendations for such programs are offered here, because they are being planned independently.

1. Observation Objectives

We recommend that large-scale ocean and atmospheric CO_2 observations respond to the two basic questions of the CCSP by adopting the following objectives:

- To constrain natural and anthropogenic CO_2 fluxes between the land biosphere and atmosphere on the scales of continents and of coherent ecosystems within continents (on the order of 10^3 km), and between the ocean and atmosphere on the scale of ocean basins. The focus will initially be on constraining climatologic (average) fluxes at scales of continents and ocean basins, and seasonal fluxes at the scales of coherent continental ecosystems. It will extend to studies of interannual variability as observation systems develop and models improve.

- To provide data sets that challenge models of the land biosphere and atmospheric transport, on the one hand, and models of gas exchange and ocean mixing, on the other. Current models of the land biosphere and atmospheric transport will improve when model predictions are compared with detailed data on CO_2 distributions. Similarly, ocean circulation models will improve as their predictions are compared with data on the evolving distribution of anthropogenic CO_2 and other transient tracers in the ocean.

- To improve process-level understanding of the controls on biogeochemical cycling on land and in the oceans. Variations in concentrations of CO_2, O_2, and related properties, interpreted using transport models, constrain ecosystems' productivity. We can use observations of these properties to track the evolving response to such physical forcings as weather and climate over the continents, upper ocean mixing, and nutrient supply in the oceans. The relationship between forcing and response provides process-level information and improves our understanding of responses to anthropogenic change.

- To track the fate of anthropogenic CO_2. A proper observing system will allow us to track the accumulating inventory of anthropogenic CO_2, not only in the atmosphere but also in the ocean and land biosphere as well.

- To enhance our ability to predict the evolution of the atmospheric CO_2 burden.

To date, scientists have addressed these questions with three sets of large-scale observations in the oceans and atmosphere. The first involves observations of CO_2 in the atmosphere. These observations directly record the anthropogenic CO_2 inventory in air. Comparing the rate of atmospheric CO_2 increase with rate of combustion gives the summed rate of CO_2 sequestration by the land and the oceans. Regional variations in the CO_2 concentration of air, interpreted using transport models, constrain the CO_2 uptake rate by the land biosphere and the oceans. Variations in the O_2/N_2 ratio of air and the $\delta^{13}C$ of CO_2 allow us to partition sequestration between the land biosphere and the oceans. Constraints currently apply to scales on the order of 10^4 km. As data density increases and models improve, we are gaining the ability to work at smaller scales.

The second observation set contains measurements of the partial pressure of CO_2 (pCO_2) in surface seawater. The air-sea pCO_2 difference, together with the gas exchange coefficient, gives the air-sea flux of CO_2. The global air-sea flux, annually averaged, constrains the rate at which the oceans take up anthropogenic CO_2. Spatial and seasonal variations in air-sea fluxes reflect the sum of carbon fluxes due to anthropogenic CO_2 uptake, ocean circulation, biogeochemical transformations, and ocean heat fluxes. Sea surface pCO_2 data give basic information about each of these processes. Controlling processes are reflected in satellite data, which can then be used to scale up the local observations.

The third data set describes the distribution of CO_2 in the ocean interior. This property largely reflects the interaction of biological carbon fluxes, which induce depth and flow-line gradients in CO_2, and ocean circulation, which mixes water and dissipates those gradients. Superimposed on natural variations are the smaller variations in anthropogenic CO_2 concentrations. These can be teased out by using analysis techniques that rely in part on measured concentrations of other bioactive tracers (e.g., O_2). Resulting maps of the anthropogenic CO_2 distribution record both regional uptake of CO_2 at the sea surface and the effects of ocean currents in transporting and redistributing the oceanic burden.

Each of these data sets makes a unique contribution to our understanding of the ocean carbon cycle, both natural and anthropogenic. Each gives essential information about fluxes of anthropogenic CO_2, current CO_2 inventories, and the nature of processes responsible for ocean and land sequestration. Each also gives rates of air-sea or air-land CO_2 fluxes that are largely or completely independent of estimates from the other approaches at the various scales. For these reasons, we recommend that the observation system evolve as a balanced entity that continues to rely on CO_2 observations in all three realms: atmosphere, sea surface, and ocean interior. Redundant measures of carbon fluxes are also essential for confidently closing the mass balance, because calculations of anthropogenic carbon fluxes all have large uncertainties.

Models of transport and biogeochemistry are essential tools for interpreting the distribution of CO_2 and deducing carbon fluxes in the three major observation realms. We make a series of recommendations for improving skills of relevant models. One aspect of the recommendations involves collection of data that can challenge models, particularly models describing the CO_2 distribution in the continental planetary boundary layer, but ocean models as well. We also make recommendations for improvement to model structure and approaches that will lead to improved representation of basic processes and more accurate calculation of fluxes. A particular emphasis will be on including data assimilation methods in carbon cycle models. In general, our implementation plan considers that progress will be made only with close interactions between observations and modeling. Results from one will lead to improvements in the other.

Following recommendations of the U.S. Carbon Cycle Science Plan, we recommend the following observational strategy: (1) atmospheric studies focusing on North America, (2) sea surface pCO_2 studies focusing on the surrounding ocean basins (North Atlantic and North Pacific) and the Southern Ocean, and (3) ocean interior studies that center on the global scale, with the primary objective of constraining the distribution of anthropogenic CO_2 in the world's oceans.

The technology for measuring CO_2 and related properties is evolving rapidly, as are models that describe their distributions and allow us to estimate source and sink strengths. We therefore recommend an initial 5-year program for atmosphere and sea surface studies. We recommend a 10-year program for ocean interior studies, which involve sampling by oceanographic research ships, a more mature technology.

2. Selected Ongoing Programs

We strongly recommend vigorous support for selected major ongoing U.S. programs to study the distribution of CO_2 and related properties in the atmosphere and oceans. These programs include flask sampling measurements of CO_2, O_2/N_2, $\delta^{13}C$ of CO_2, and related properties in air; repeat measurements of sea surface pCO_2 on oceanographic ships of opportunity; and measurements of biogeochemical properties at the sea surface and in the ocean interior at time-series study sites such as the Bermuda Atlantic Time Series site and the Hawaii Ocean Time Series site.

3. Recommended New Programs

We recommend the following new programs as high priority:

1. **Detailed measurements of atmospheric CO_2 over North America to improve understanding of the productivity of the land biosphere and our knowledge of CO_2 sequestration on the continent. Also, development of a new CO_2 analyzer for atmospheric measurements to improve the data and facilitate the measurement program.**

We recommend an intensive series of measurements of CO_2 and related properties over North America, made utilizing tall towers, vertically profiling aircraft, and aircraft sampling campaigns covering broad reaches of the continent. This work will give detailed CO_2 data, challenging models of the land biosphere and atmospheric circulation. The data, together with model improvements, will produce major advances in characterizing land ecosystem activity and the sequestration of CO_2 on the continent.

2. **Studies of the sea surface partial pressure of CO_2 (pCO_2) and air-sea fluxes in the North Atlantic, North Pacific, and Southern Ocean, to determine biogeochemical fluxes and constrain anthropogenic CO_2 uptake by these basins.**

We recommend a major expansion of sea surface pCO_2 measurements and related properties in the North Atlantic, North Pacific (including the equatorial Pacific), and the Southern Ocean. The measurements will be made primarily using volunteer observing ships, supplemented by moored samplers and other programs. The North Atlantic and North Pacific studies will yield constraints for improved estimates of the North American carbon sink, robust values of air-sea CO_2 fluxes in Northern Hemisphere oceans, and extensive new information about biogeochemical fluxes in the basins. The equatorial Pacific studies will provide measures of air-sea fluxes in a region that accounts for a large fraction of ocean interannual variability. The Southern Ocean work will improve understanding of climatological fluxes in this region. It will also give insight into the carbon cycle of this ocean, which is an undersampled region widely regarded as susceptible to global change.

Calculating air-sea fluxes from sea surface pCO_2 data requires values for gas exchange coefficients. These coefficients are now characterized in terms of wind speed and are highly uncertain. We recommend process studies to more accurately characterize gas exchange coefficients, in terms of wind speed or other properties observed globally by satellites at high resolution.

3. Systematic studies of CO_2 and related properties in the ocean interior, to characterize ocean mixing and map the distribution of fossil fuel CO_2.

We recommend that 15 ocean sections, spanning all major basins, be resampled every 10 years for hydrographic and geochemical properties. The results will document the evolving inventory and distribution of fossil fuel-derived CO_2 in the ocean, constrain the distribution of surface ocean uptake, and serve as a constraint for ocean circulation models that predict the distribution of transient tracers.

These observations, along with the results of complementary process studies, and interpreted in the context of prognostic models, will lead to major advances in knowledge of the following topics:

- Fluxes and distribution of anthropogenic CO_2.
- Ocean and atmosphere mixing patterns.
- Biosphere processes that regulate CO_2 uptake on land and in the oceans.
- The expected future evolution of atmospheric CO_2.

4. High-resolution time series studies of biogeochemical properties of the ocean using moored sensors.

We recommend an aggressive program of developing, testing, and installing autonomous sensors of CO_2 parameters and other biogeochemical properties on moorings to make high-resolution measurements in waters of the ocean interior. The time series will inform us about the biogeochemical response to interannual and decadal timescale variability in ocean physics, giving process-level insight, and improving our understanding of the biogeochemical response to global change.

We also recommend one additional activity:

5. Preparation of a biennial report that summarizes the status of carbon cycle studies and the known status of the carbon cycle itself.

This report will have several functions:

- Summarizing the behavior of the global carbon cycle, with emphasis on recent results and on North America.
- Making the results of CO_2 observations and process studies available.
- Informing readers about the scope of ongoing observations, process studies, and modeling efforts.

The following tables (E-2 through E-4) summarize the recommendations from the observations chapters (Chapters 2, 3, and 4). Note that although the modeling and state of the carbon cycle assessments will require a significant level of investment, this report does not focus on delineating specifics nor the costs of those needs and they are not included in the tables. If desired, a future community group may choose to focus specifically on those needs and how much they would cost.

Table E-2: Priorities and cost estimates for surface observation program.

Element of the implementation plan	Priority	Ship time	Costs/year
Recommendations for the Next 1 to 5 Years*			
Form and improve international collaborations on unified data protocols	1		$300,000
Measure pCO_2 and related properties on volunteer observing ships			
VOS studies in the North Atlantic (4 ships)	1		$520,000
VOS studies in the Southern Ocean (existing/new 4 ships)	1/2		$600,000
VOS studies in the equatorial Pacific (2 ships)	1/2		$300,000
VOS studies in the equatorial and North Pacific (2 ships)	2		$600,000
Meridional trans-Atlantic and trans-Pacific lines (4 ships)	3		$150,000
Measurements of ancillary properties (5 ships)	1–5		$1,000,000
Improve our understanding of the physics of gas exchange			
Longer term observations	1		$750,000
Upscaling studies	2		$350,000
Process studies	3	$1,000,000	$1,500,000
Deploy moorings for time series of pCO_2 and related biogeochemical properties			
Time-series stations at HOT and BATS (including mooring)	1		$2,000,000
Equatorial Pacific time series (4 systems, excluding cost of moorings)	1		$600,000
Boreal time series in the North Atlantic and North Pacific (including mooring)	2	$1,000,000	$2,000,000
Time-series sites in the Southern Ocean (including mooring)	4	$1,000,000	$2,000,000
Design a data access system	2		$400,000
Develop improved autonomous sensors for sea surface analysis			
Develop improved autonomous sensors for sea surface analysis of pCO_2	2		$400,000
Develop for measurement of ancillary properties	3		$1,000,000
Develop formalisms for interpolating air-sea CO_2 fluxes in time and space	3		$300,000
Deploy drifters with pCO_2 sensors to map pCO_2 fields			
Southern Ocean drifters (20)	4	$1,000,000	$1,200,000
Subpolar/subtropical North Atlantic drifters (20)	4	$360,000	$1,200,000
Equatorial Pacific drifters (20)	4	$450,000	$1,200,000

*Results from years 1–5 will be used to plan for a comprehensive sea surface pCO_2 observing system 5 years hence as measurement technologies, modeling capabilities, and knowledge of ocean pCO_2 are improved.

Table E-3: Priorities and cost estimates for the interior ocean program.

Element of the implementation plan	Priority	Ship time* ($/year)	Science ($/year)
First 5-Year Period			
Meridional and Zonal Sections (Atlantic and Pacific Oceans)	1	$2,000,000	$2,100,000
Augmenting HOT, BATS, and Equatorial Pacific with autonomous sensors	1	$500,000	$1,500,000
Augmenting high-latitude time-series sites with CO_2 measurements	2	$500,000	$1,100,000
Develop/improve sensors for measurements of two CO_2 system properties	2		$500,000
Second 5-Year Period			
Meridional and Zonal Sections (Southern Oceans)	1	$1,500,000	$2,200,000
Meridional and Zonal Sections (Atlantic, Pacific, and Indian Oceans)	1	$1,500,000	$1,500,000
Augmenting Southern Ocean time-series sites with autonomous sensors	1	$500,000	$1,500,000
Instrumented profiling floats and gliders	2	$800,000	$1,500,000
Augmenting tropical and subtropical time-series sites with autonomous sensors	3	$500,000	$1,500,000

*Ship-time costs are estimated at $20,000 per day.

Table E-4: Summary of observation plan costs.*

	One-time Costs	Annual Costs	Annual Ship Cost
1–5 Years			
Priority 1			
Atmospheric Observations	\$1,250,000	\$4,625,000	
Surface Ocean Observations		\$6,070,000	
Ocean Interior Observations		\$3,600,000	\$2,500,000
Subtotals	**\$1,250,000**	**\$14,295,000**	**\$2,500,000**
Priority 2			
Atmospheric Observations	\$5,300,000	\$10,000,000/campaign \$7,800,000	
Surface Ocean Observations		\$4,250,000	\$1,000,000
Ocean Interior Observations		\$1,600,000	\$500,000
Subtotals	**\$5,300,000**	**\$13,650,000 w/o campaign**	**\$1,500,000**
Priority 3+			
Atmospheric Observations	\$1,290,000	\$1,840,000	\$15,000/ship (pCO_2 platforms)
Surface Ocean Observations		\$8,550,000	\$3,810,000
Ocean Interior Observations			
Subtotals	\$1,290,000	\$10,390,000	\$15,000/ship
Totals	\$7,840,000	\$38,335,000 + \$10,000,000/campaign	\$4,000,000 + 15,000/ship
6–10 Years			
Priority 1			
Atmospheric Observations	\$15,000,000	\$15,000,000	
Surface Ocean Observations			
Ocean Interior Observations		\$5,200,000	\$3,000,000
Subtotals	**\$15,000,000**	**\$20,200,000**	**\$3,000,000**
Priority 2			
Atmospheric Observations			
Surface Ocean Observations			
Ocean Interior Observations		\$1,500,000	\$800,000
Subtotals	**N/A**	**\$1,500,000**	**\$800,000**
Priority 3+			
Atmospheric Observations			
Surface Ocean Observations			
Ocean Interior Observations		\$1,500,000	\$500,000
Subtotals		**\$1,500,000**	**\$500,000**
Totals	**\$15,000,000**	**\$23,200,000**	**\$4,300,000**

*Note that modeling costs and costs associated with the biennial report on the state of the carbon cycle are not included, as this report did not focus on delineating the specifics and costs of those needs.